

The Soft-Wall Standard Model *

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- arXiv:0808.3977

Outline

- Warped dimension and hierarchies
- AdS/CFT duality and compositeness
- Hard vs. Soft walls
- Soft-wall dynamics
- Soft wall electroweak models

Big Question : How do particles get mass?

- We think there is a Higgs boson waiting for us at the LHC
- but ... Hierarchy Problem - Higgs mass sensitive to quantum effects

$$m_{Higgs}^2 = m_0^2 + c\Lambda^2$$

- Suppose no new physics until Planck scale, $\Lambda \sim 10^{19}$ GeV:

$$(10^2 \text{GeV})^2 = m_0^2 + (10^{19} \text{GeV})^2$$

- \Rightarrow bare mass m_0 finely tuned

?

A “radical” solution

Warped extra dimension

Randall, Sundrum '99

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$$

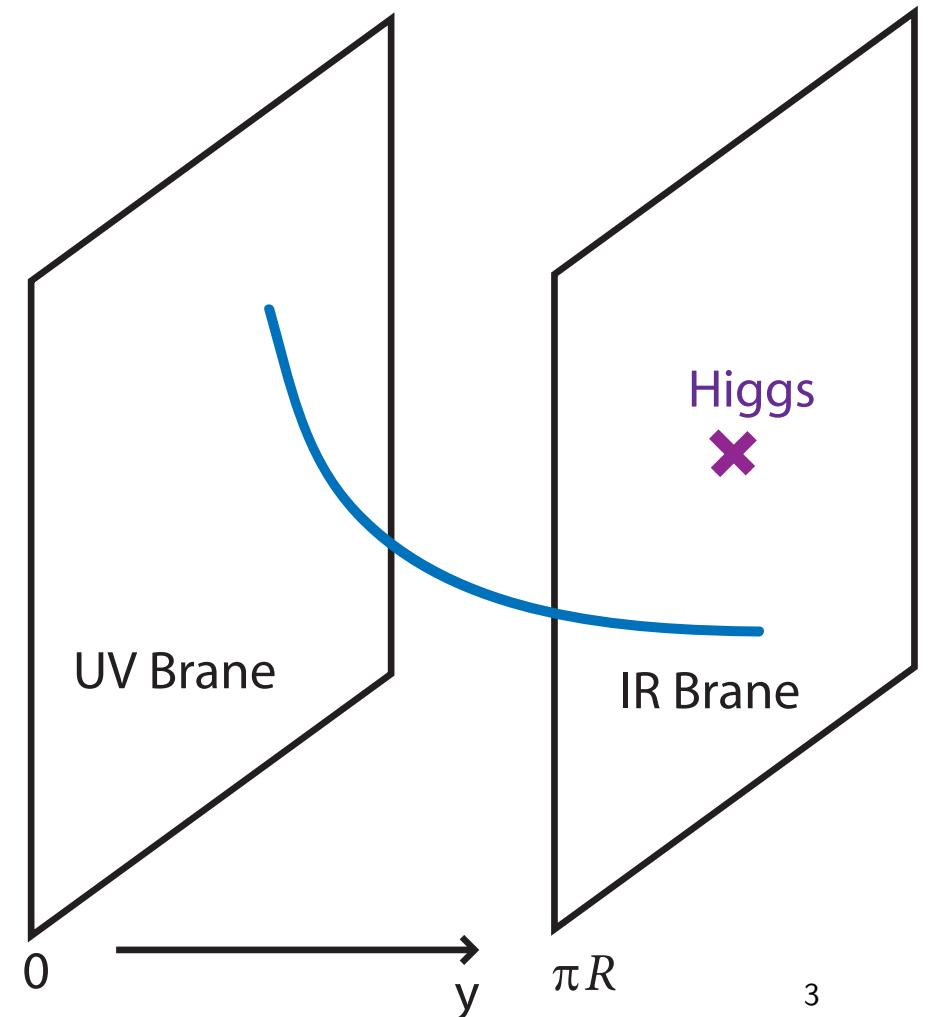
- Warped geometry \implies
Energy scales depend on location
- Planck/Weak scale hierarchy:

$$\Lambda_{weak} \sim M_P e^{-\pi k R}$$

$$k \sim \mathcal{O}(M_P), \quad \pi k R \sim \mathcal{O}(30)$$

- R can be naturally stabilized

Goldberger, Wise '99



Standard model in the bulk

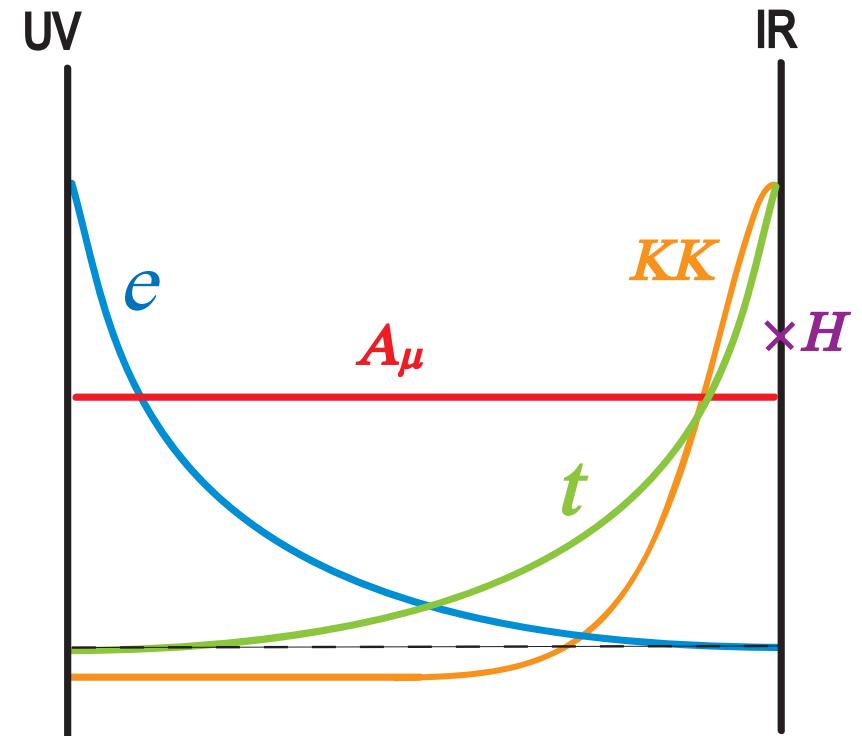
Davoudiasl, Hewett, Rizzo '99; Pomarol '99

Grossman, Neubert '99

Chang et al. '99; Gherghetta, Pomarol '00

Theory of Flavor!

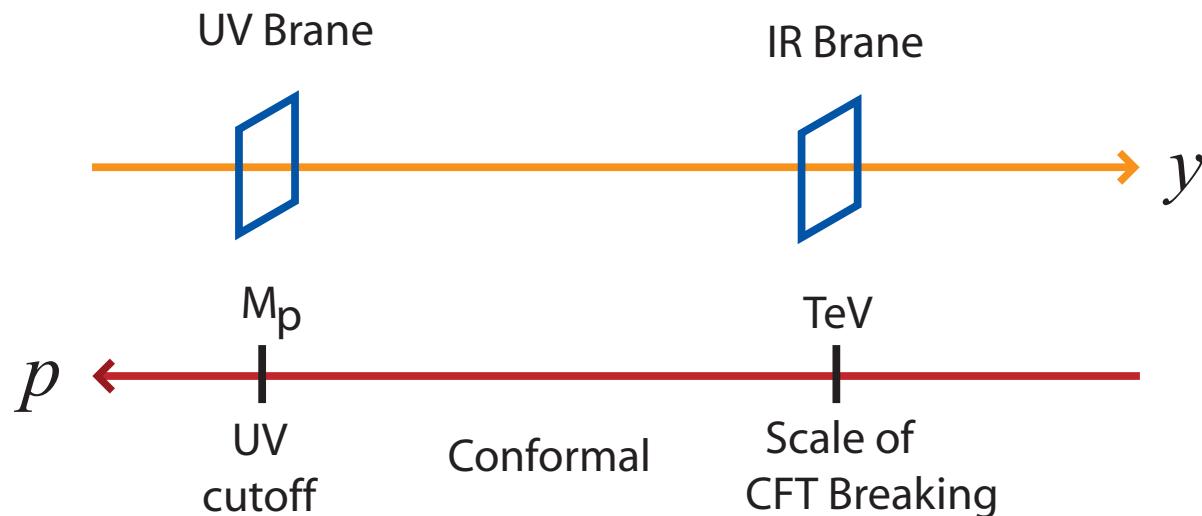
- Natural Yukawa hierarchies
- FCNC suppressed



Electroweak tests $\implies M_{KK} \sim 3 \text{ TeV}$

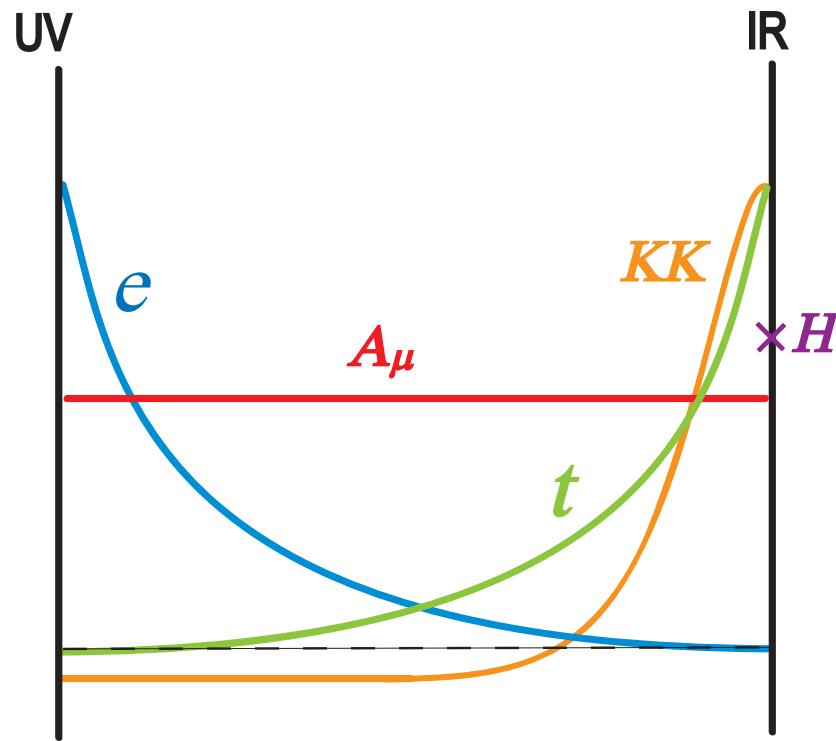
Holography for RS1 via AdS/CFT

Arkani-Hamed, Poratti, Randall '00
Rattazzi, Zaffaroni '00
Perez-Victoria '00



zero mode	\sim	source field (elementary)
KK modes	\sim	CFT bound states (composites)

Partial compositeness of SM fields

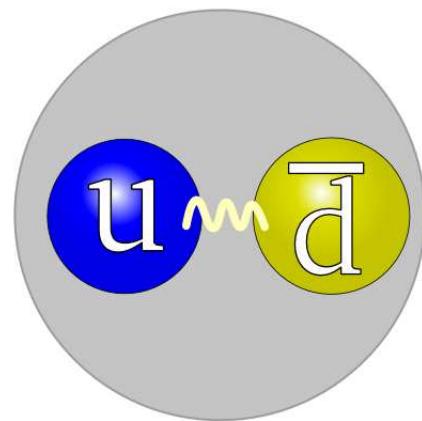


- UV localized \iff mostly elementary
- IR localized \iff mostly composite

A “conservative” solution

Compositeness (Strong gauge dynamics)

- Quantum Chromodynamics:
 - $SU(3)_{color}$; quarks and gluons
 - Confinement at $\Lambda_{QCD} \sim 200\text{MeV}$
 - We observe composite particles,
e.g. Pion



Could the Higgs (or something like it) be composite, with $\Lambda \sim \text{TeV}$?

- Technicolor Weinberg; Susskind '70s
- Composite Higgs Kaplan,Georgi '80s

Take-home message:

Use warped extra dimension to model
electroweak symmetry breaking
with strong gauge dynamics!

- But . . . is Randall-Sundrum “hard-wall” model the only way?

Soft wall AdS/QCD

Karch, Katz, Son, Stephanov '06

- Confinement achieved with dilaton instead of IR brane

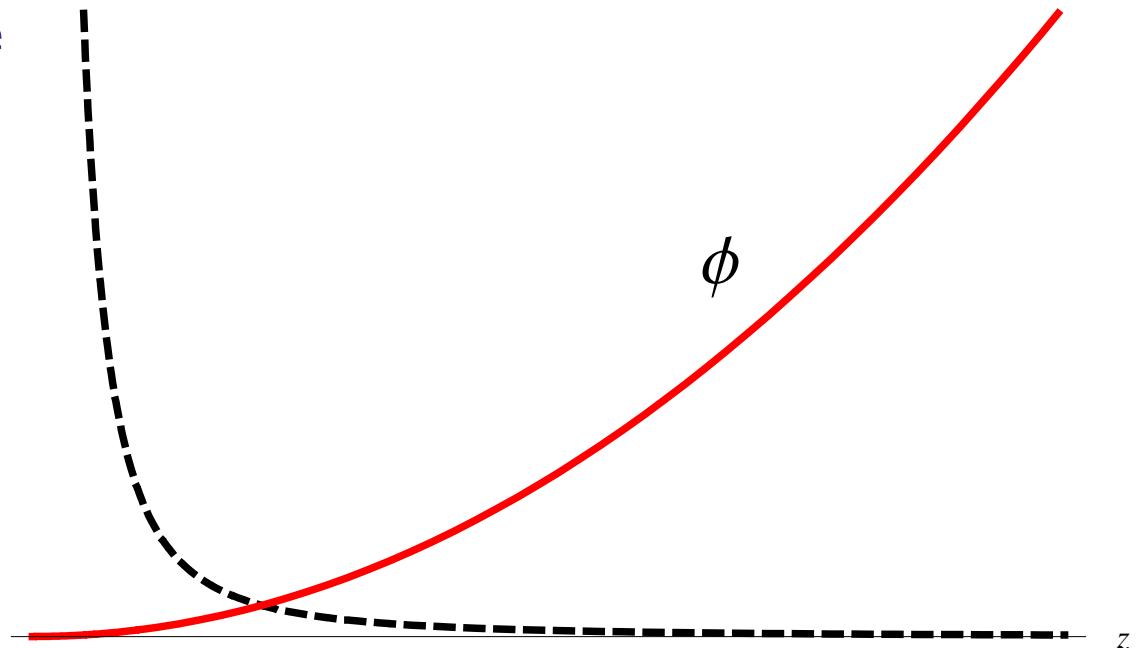
$$S = \int d^4x dz \sqrt{-g} e^{-\Phi} \mathcal{L}$$

- Simplest model:

$$\begin{aligned} g_{MN} &= z^{-2} \eta_{MN} \\ \Phi(z) &= z^2 \end{aligned}$$

- Regge trajectories:

$$m_n^2 \sim n$$



Soft-wall dynamics

How could this background arise dynamically?

BB, Gherghetta '08

- Factor $e^{-\Phi}$ in arises from open string/D-brane sector
- Start from string inspired action including closed string tachyon:

$$S = M^3 \int d^5x \sqrt{-g} e^{-2\Phi} \left(R + 4g^{MN} \partial_M \Phi \partial_N \Phi - \frac{1}{2} g^{MN} \partial_M T \partial_N T - V(\Phi, T) \right)$$

- What about the potential $V(\Phi, T)$? Don't know *a priori* so work backwards

Solution

$$\begin{aligned}\Phi(z) &= z^\nu, \\ T(z) &= \pm 4\sqrt{1 + 1/\nu} z^{\nu/2}, \\ g_{MN} &= \frac{\eta_{MN}}{z^2}\end{aligned}$$

$$\tilde{V}(\phi, T) = \frac{T^2}{2} e^{T^2/18} + 2\phi^2 e^{2\phi/\sqrt{6}} - 12 \left[3e^{T^2/36} - 2 \left(1 - \frac{\phi}{\sqrt{6}} \right) e^{\phi/\sqrt{6}} \right]^2$$

- Pure AdS metric and power-law dilaton
- $\nu = 2$ yields linear trajectories
 \implies realizes KKSS AdS/QCD model
- Potential is exotic, but $e^{2\phi/\sqrt{6}}$ matches 5D noncritical string theory

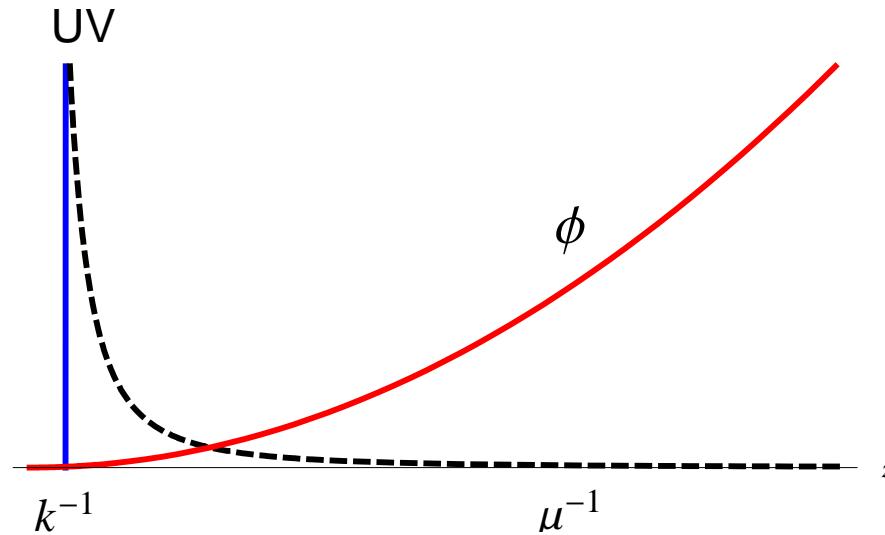
Electroweak physics with a soft wall

Falkowski, Pérez-Victoria '08
BB, Gherghetta, Sword '08

- Require UV brane to obtain normalizable zero modes
- Use dynamical solution:

$$g_{MN} = \frac{\eta_{MN}}{(kz)^2}$$
$$\Phi(z) = (\mu z)^\nu$$

- Introduce scales:
 - $M \sim k > \mu$
- Note μ is a modulus



Bulk fields

- In general, eigenmodes obey 1D “Schrödinger” equation

$$(-\partial_5^2 + V(z)) f^n(z) = m_n^2 f^n(z)$$

- At large z , find power-law potential:

$$V(z) \sim \mu^4 z^{2\nu-2}$$

- WKB approximation yields discrete spectrum ($\nu > 1$):

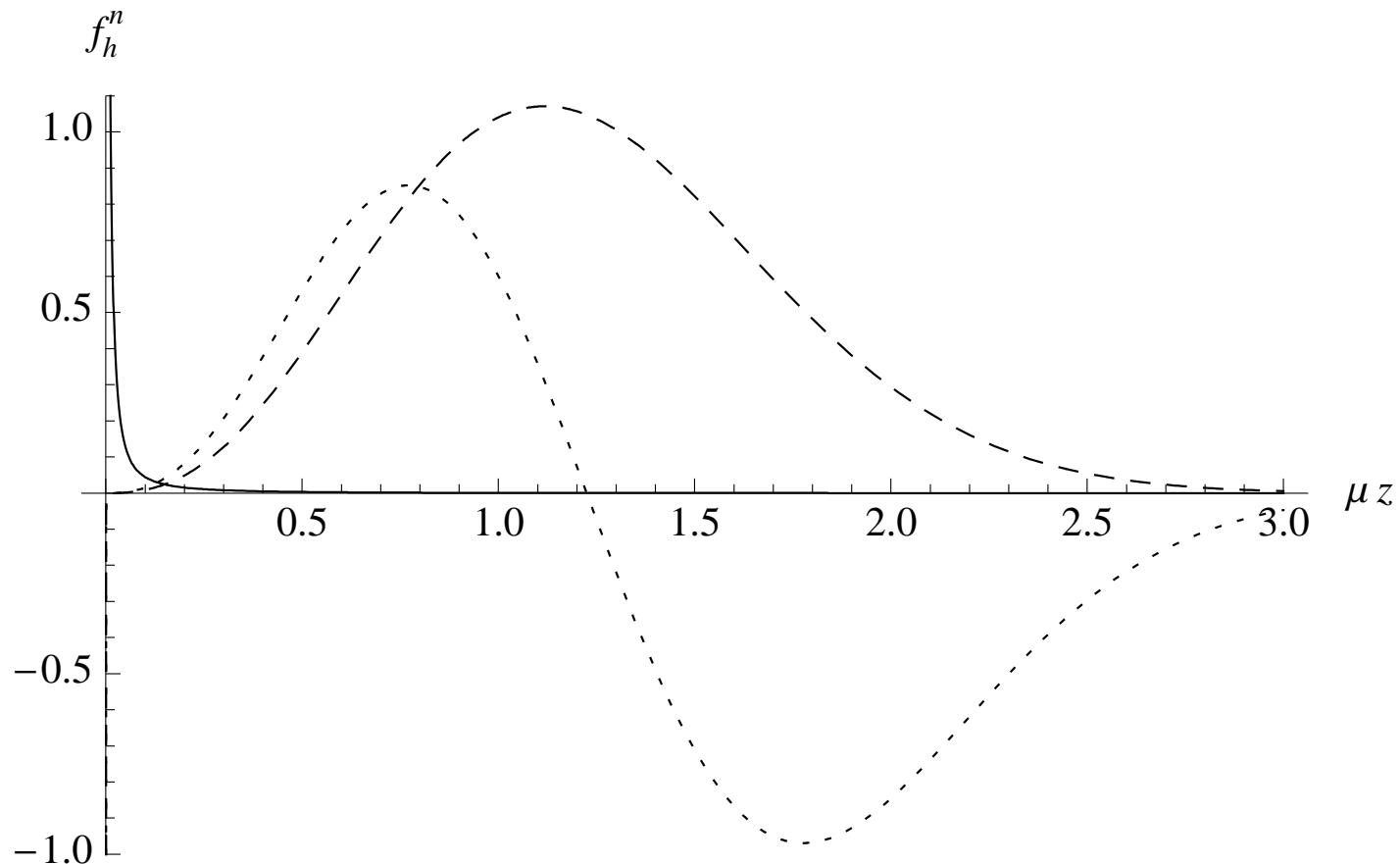
$$m_n^2 \sim \mu^2 n^{2-2/\nu}$$

- Continuum for $\nu \leq 1$ (Unparticles, hidden valley)

Examples: graviton fluctuations $h_{\mu\nu}(x, z)$ ($\nu = 2$)

$$V_h(z) = 4\mu^4 z^2 + 4\mu^2 + \frac{15}{4z^2}$$

$$m_n^2 \simeq 8\mu^2(n+1), \quad n = 1, 2 \dots$$



Gauge field $A_\mu(x, z)$

$$S = \int d^5x \sqrt{-g} e^{-\Phi} \left(-\frac{1}{4} F_{MN} F^{MN} \right)$$

$$\begin{aligned} V_A(z) &= \mu^4 z^2 + \frac{3}{4z^2} \\ m_n^2 &\simeq 4\mu^2 n, \quad n = 1, 2 \dots \end{aligned}$$

Wavefunctions similar to gravitons

Fermions $\Psi(x, z)$

- Zero mode approximation: treat Yukawa interactions as perturbation
- But ... with a soft wall, Higgs is a bulk field and grows at large z
⇒ Must solve coupled system!

$$S_{Yukawa} = - \int d^5x \sqrt{-g} e^{-\Phi} \left[m^{ij}(z) \bar{\Psi}_L^i(x, z) \Psi_R^j(x, z) + \text{h.c.} \right]$$
$$m^{ij}(z) \equiv \frac{\lambda_5^{ij}}{\sqrt{2k}} h(z)$$

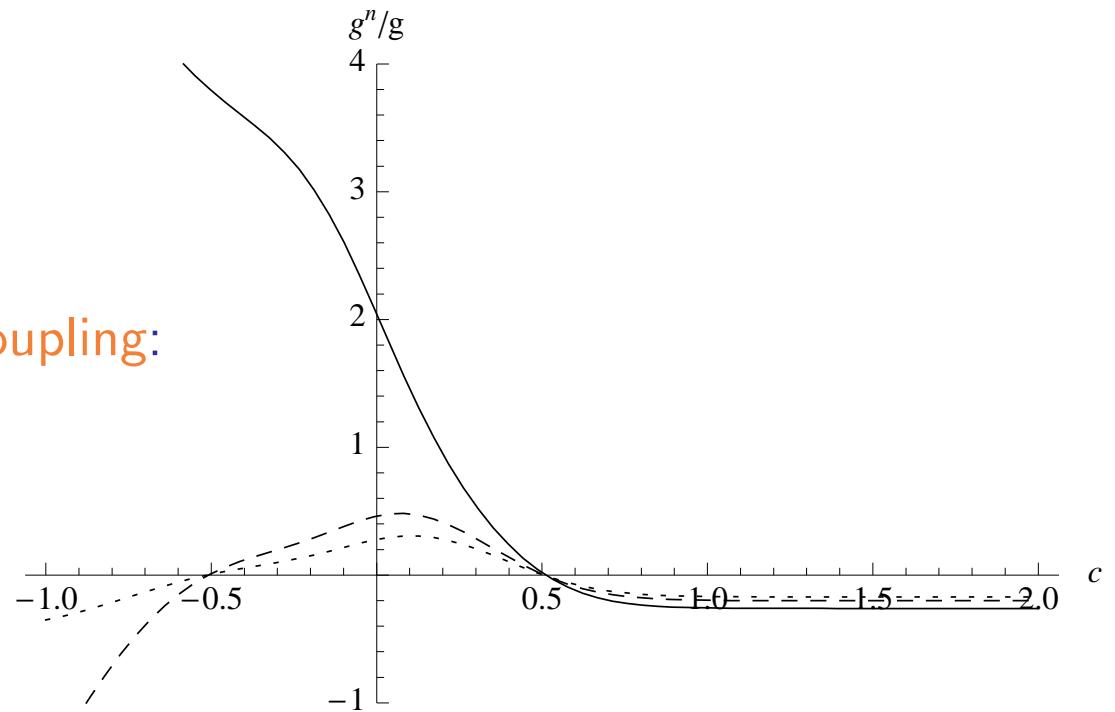
- $h(z)$ is Higgs VEV e.g. $h(z) \sim (\mu z)^2$
- In general, cannot solve system analytically since mass mixing is z -dependent

Fermions $\Psi(x, z)$ cont.

- Toy model: Single generation with $M_L = M_R = ck$
 \implies Possible to analytically solve eigenfunctions and spectrum
- Obtain mass hierarchy:

$$m_0^2 \sim \mu^2 \left(\frac{\mu}{k}\right)^{-1+2|c|} \quad |c| > 1/2$$

- and Universal $\psi^0 A_\mu^n \psi^0$ coupling:



Electroweak model

- $SU(2)_L \times SU(2)_R \times U(1)_X$ in bulk
- Higgs in bulk
- Fermions on UV brane (for now)

$$S = \int d^5x \sqrt{-g} e^{-\Phi} \left[-\frac{1}{4g_5^2} L_{MN}^a L^{aMN} - \frac{1}{4g_5^2} R_{MN}^a R^{aMN} - \frac{1}{4g_5'^2} X_{MN} X^{MN} \right. \\ \left. - \text{Tr}|D_M H|^2 - V(H) \right] - \int d^4x \sqrt{-g_{UV}} e^{-\Phi} V_{UV}(H),$$

- BC break to $SU(2)_L \times U(1)_Y$ on UV brane
- $\langle H(z) \rangle$ condensate breaks $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$

Electroweak constraints

- Example:

- linear VEV $h(z) \propto z$
- UV scale $k \sim 1000 \text{ TeV}$

- Oblique parameters

$$T = 0$$
$$S \approx \frac{2\pi^3}{3g^2(\log(k/\mu) - \gamma/2)} \frac{m_W^2}{\mu^2}$$

- Demanding $S < 0.2$ implies $\mu > 500 \text{ GeV}$
- KK gauge states with masses $\sim 1 \text{ TeV}$

Conclusions

- Warped dimension \leftrightarrow EWSB with strong dynamics
- Soft wall leads to more general behavior for KK/composite states
- Electroweak constraints less severe in soft wall models
- Lots to do -
 - Hierarchy problem: Stabilization of μ + Higgs localization
 - Fluctuations of the gravity model
 - Realistic 3-generation model + Flavor
 - Collider phenomenology
 - $\nu \leq 1 \implies$ holographic unparticles
 - . . .